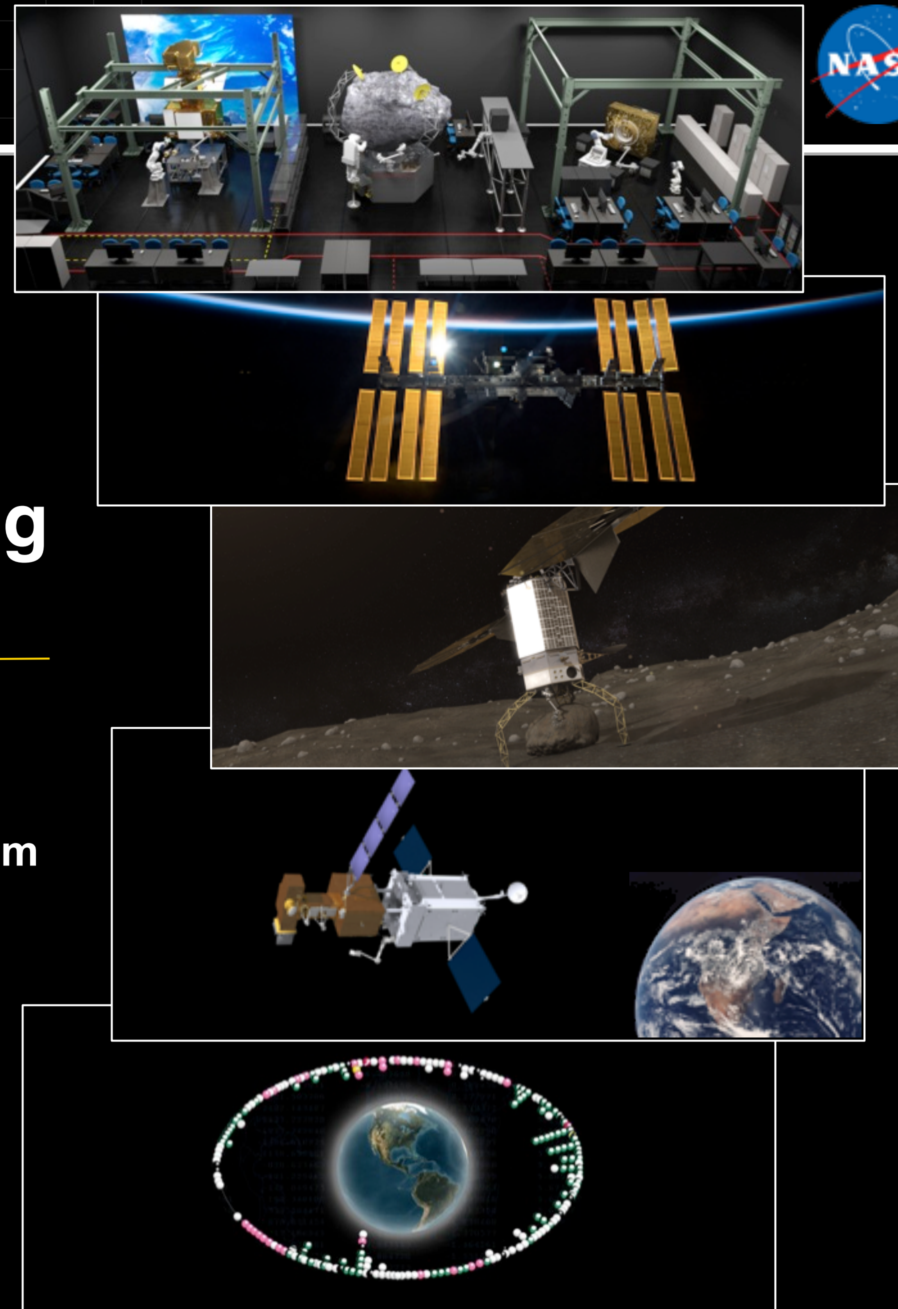
Overview of NASA's In Space Robotic Servicing

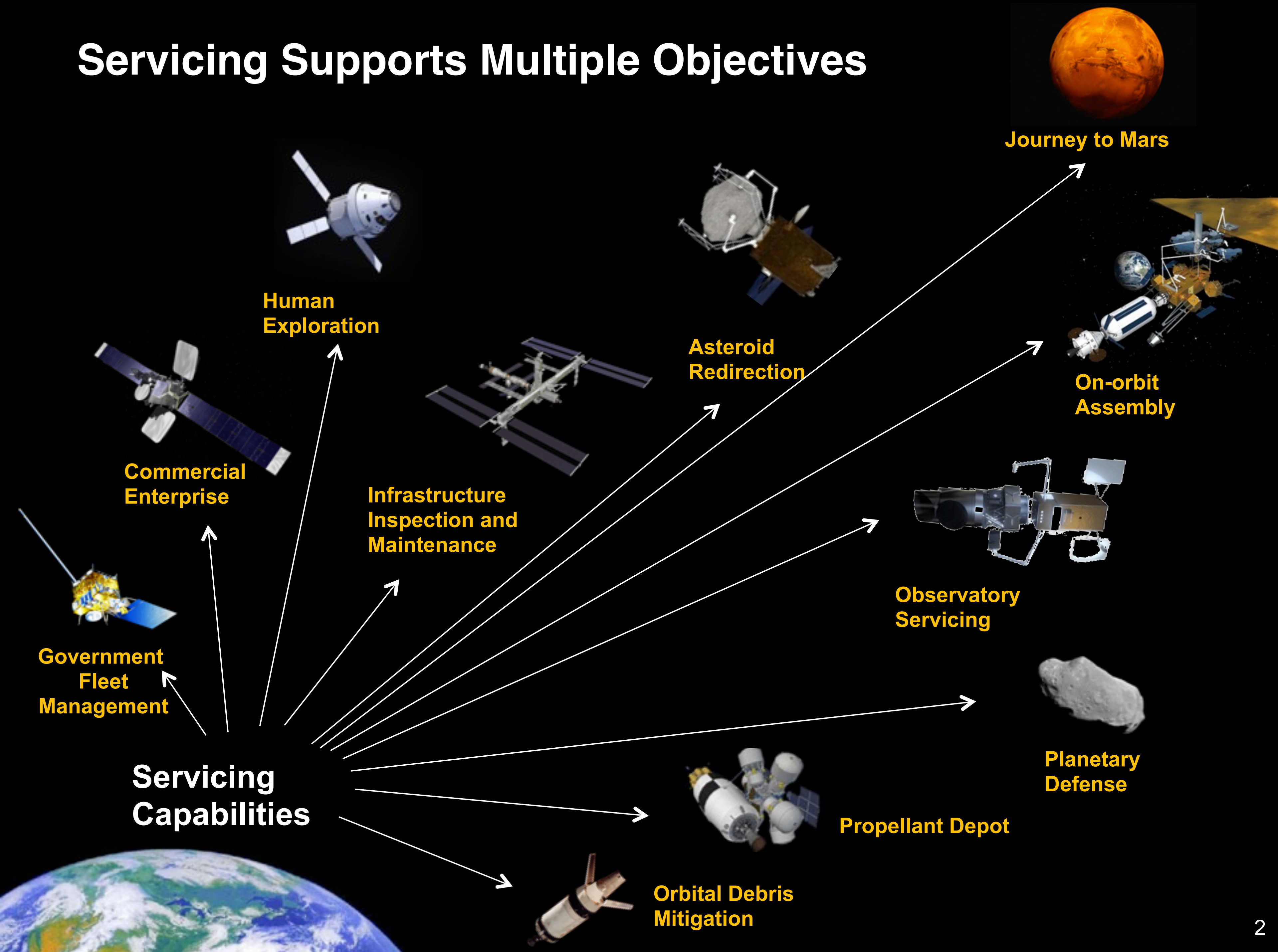


Presented to Goddard Engineering Colloquium

December 14, 2015

Benjamin B. Reed
Deputy Project Manager
Satellite Servicing Capabilities Office
http://ssco.gsfc.nasa.gov

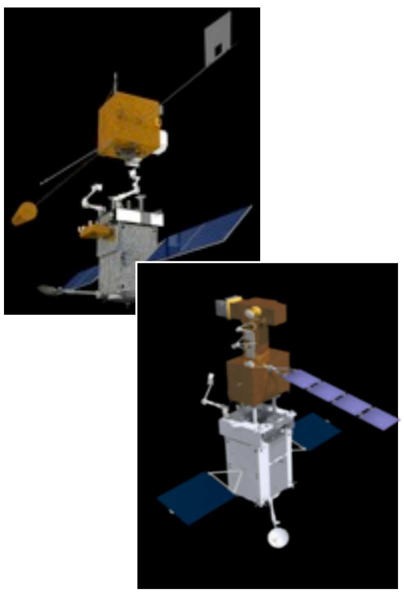
Servicing Supports Multiple Objectives



Satellite Servicing Capabilities Office (SSCO)

NASA's Satellite Servicing Capabilities Office is developing servicing technologies that support science and exploration. SSCO is responsible for the overall management, coordination, and implementation of satellite servicing technologies and capabilities for NASA. To meet these objectives we:

Study



Study point design notional missions with guidance from RFI responses

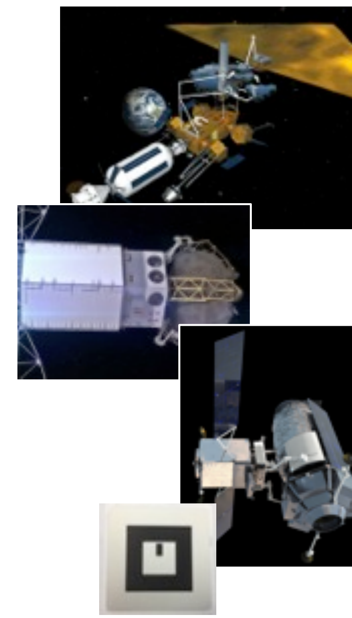
Build

Build hardware & software for experiments in orbit and on the ground

Test

Manage technology development campaign and servicing missions

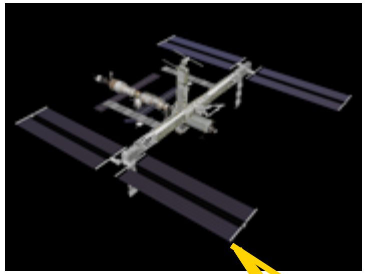
Advise



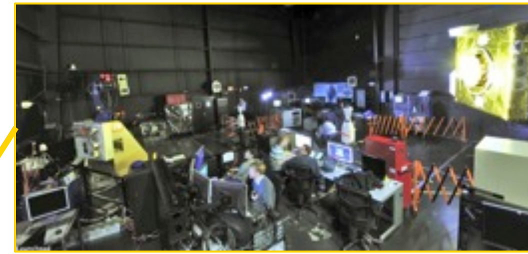
Design and advise cooperative servicing elements

In Space Robotic Servicing Team

Canadian Space Agency



Johnson Space Center

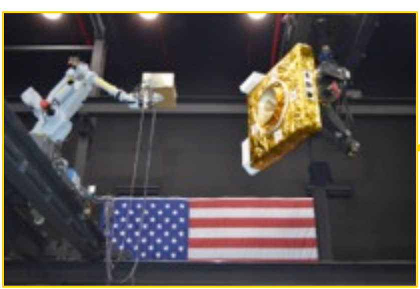


Goddard Space Flight Center

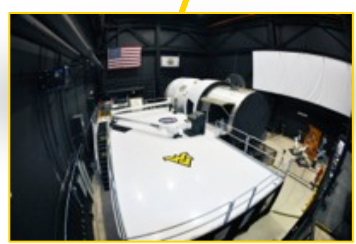
Department of Defense Space Test Program

Glenn Research Center

Lockheed Martin Space Systems Company



Naval Research Laboratory



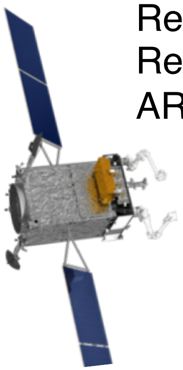
WVU JHU RPI UMD

Kennedy Space Center

What SSCO Encompasses

Servicer Designs, Capabilities, Technologies, and Beneficiaries

Legacy Servicing



Servicer

Restore-G
Restore-L
ARM

Capabilities

Remote Survey
Relocation
Refueling
Repair
Replacement
(component)

Technologies Being Matured

RPO sensors, avionics, algorithms
Dexterous robotics
High-speed, fault tolerant computing
Advanced robotic tools
Propellant Transfer System

Potential Clients

Landsat 7
Asteroid
Terra
Aqua

Cooperative Servicing

Servicer

TBD

Capabilities

Bus subsystem replacement
Instrument upgrade
Refueling

Technologies Being Matured

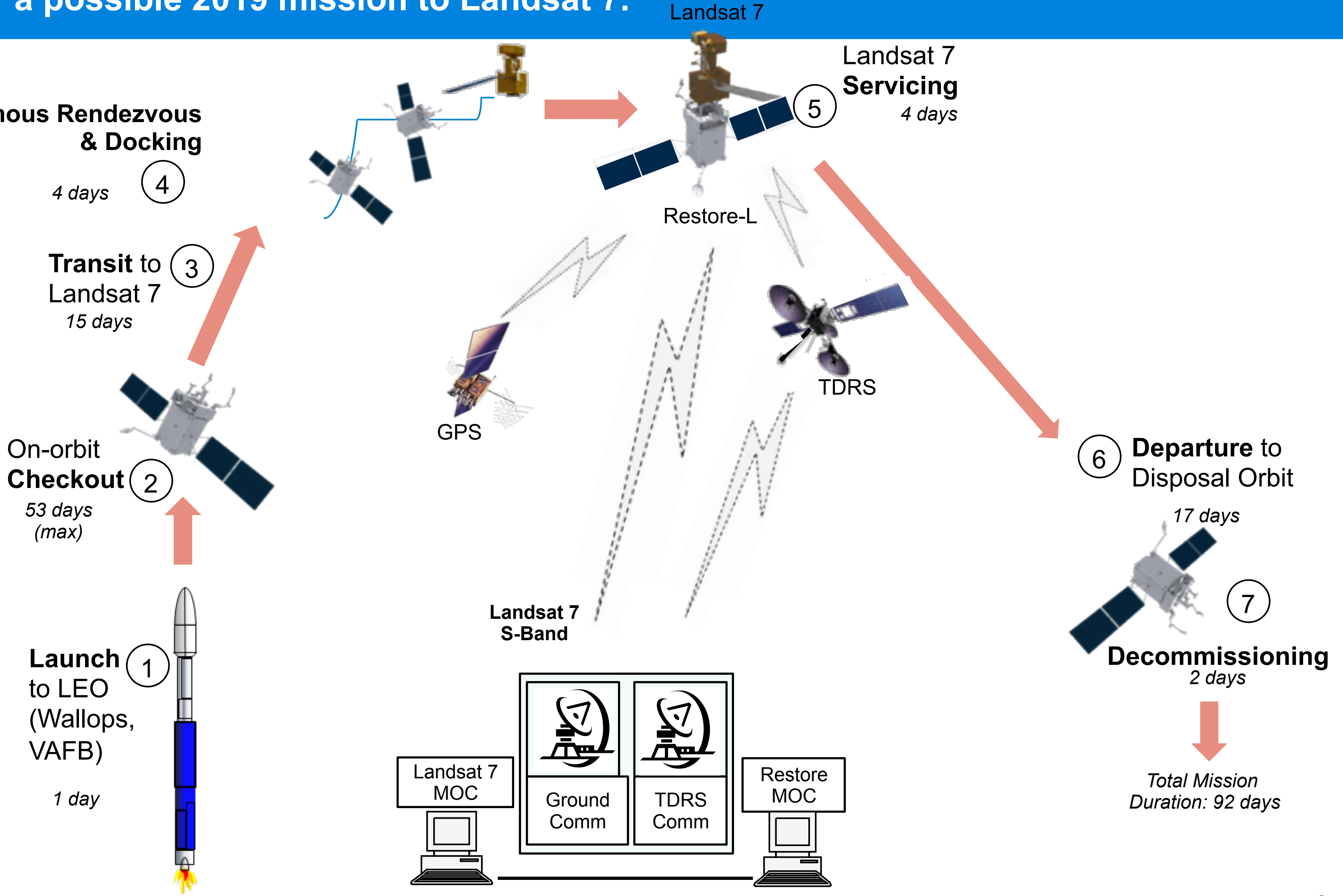
See above, plus:
Cooperative latches and fixtures
Cooperative Propellant Transfer System
Xenon transfer

Potential Clients

ROSE
MMS, JWST, GOES-R
ARM
WFIRST
LUVOIR
30-m

Overview of Notional Restore-L Mission

NASA is building and maturing the technologies needed for a possible 2019 mission to Landsat 7.



Core Technologies

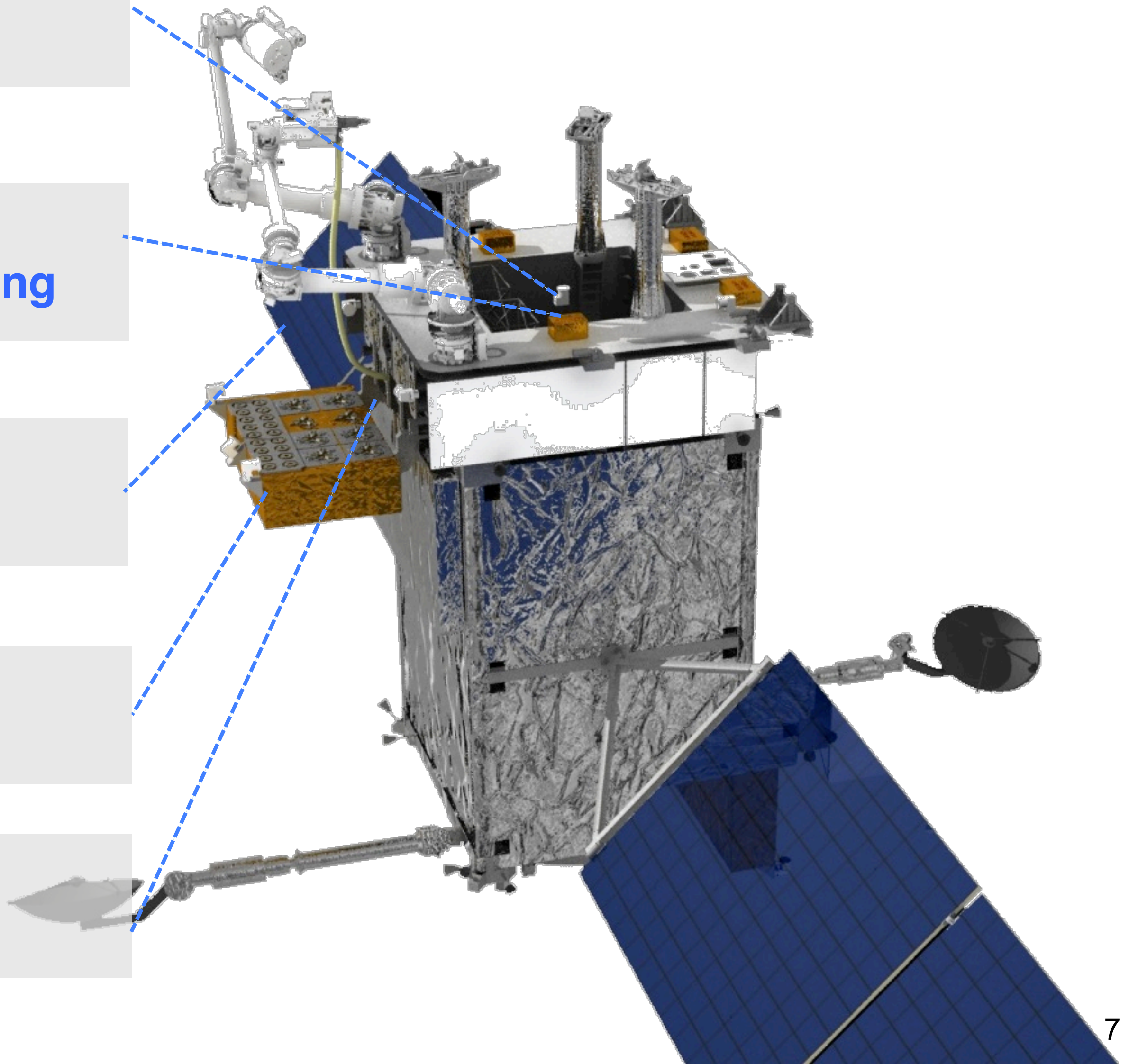
Rendezvous &
Prox Ops System

High-speed,
Fault-Tolerant Computing

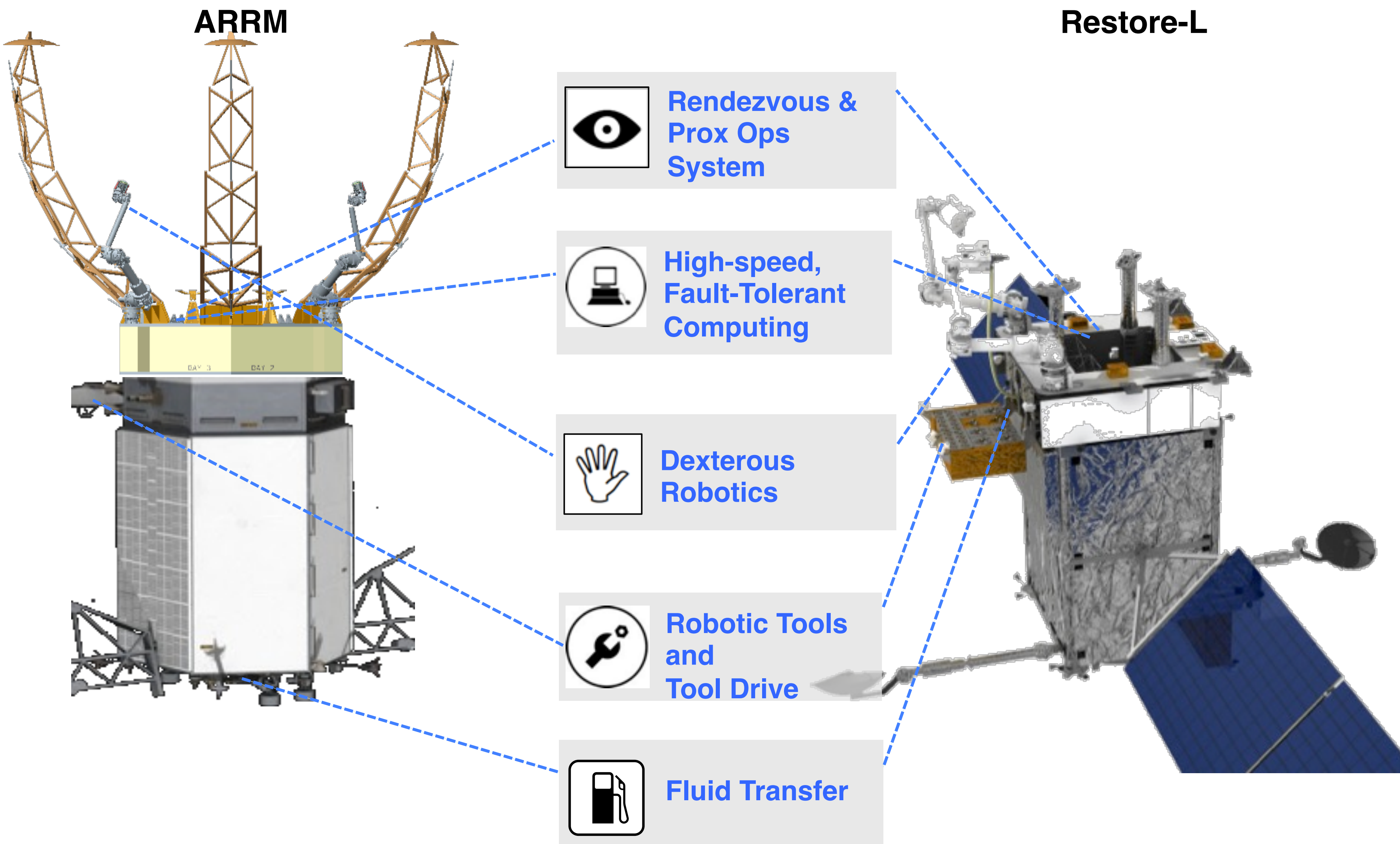
Dexterous Robotics

Robotic Tools and
Tool Drive

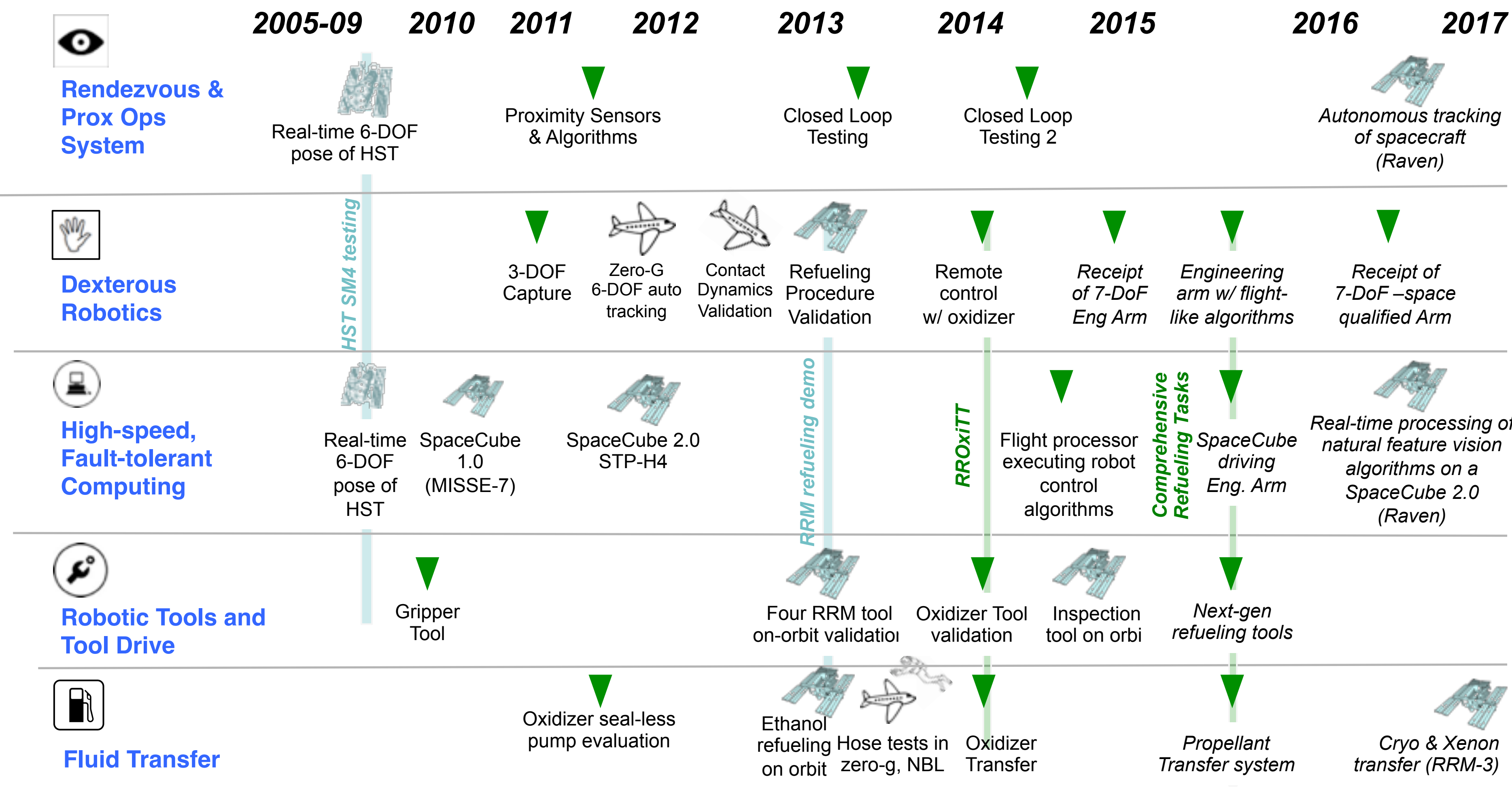
Fluid Transfer



Core Technologies
ARM and Restore-L



Steady Stream of IP to Foster a New Industry
2005 - 2017



Rendezvous and Proximity Operations
Technology Maturation and Test Campaign

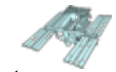
2005-2009 | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017**

Real-time 6-DOF pose of HST

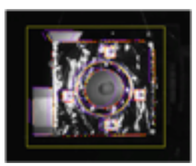
Proximity Sensors & Algorithms

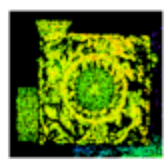
Closed Loop Testing

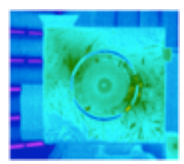
Closed Loop Testing 2



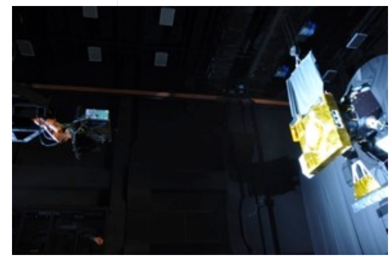
Autonomous tracking of spacecraft (Raven)



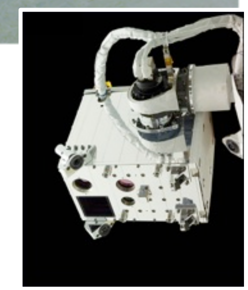




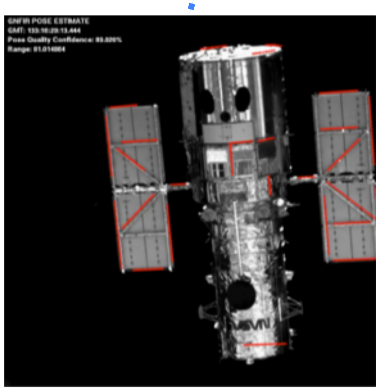
EDU (Argon) test suite demonstrated multi-wavelength (visible, flash lidar, and long-wave infrared) sensor fusion on flight avionics



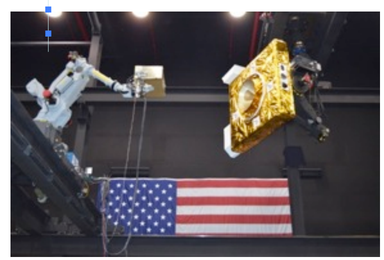
Midrange, closed-loop demonstration and high-fidelity characterization of pose algorithms and sensors



Raven demo to fly to ISS as part of DoD's STP-H5 payload



GNFIR and SpaceCube (within RNS) on STS-125: non-cooperative tracking using visible camera



Final approach and capture box closed-loop demonstration

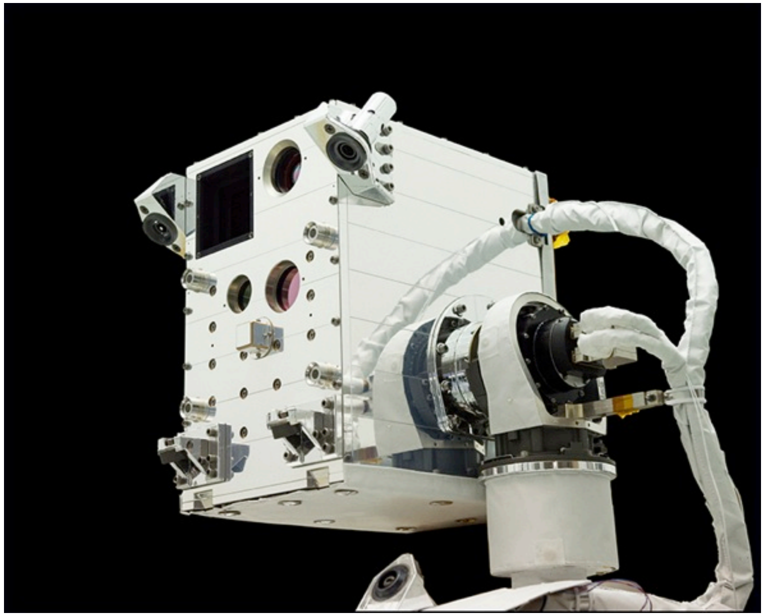
Rendezvous and Proximity Operations
Raven: Technology Demonstration on ISS

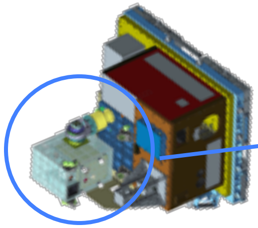
Raven is an ISS technology demonstration of system-level technologies applicable to accomplish cooperative and non-cooperative relative navigation.

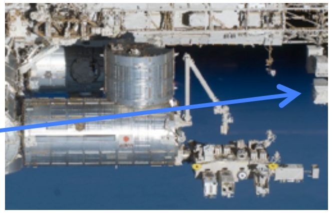
Complex, but compact, hardware complement

- Two-axis gimbal provides sensor pointing
- Relative navigation sensors provide tracking in three bands – visible, long-wave IR, and short-wave lidar
- State-of-the-art pose algorithms provide relative position and attitude measurement of the visiting vehicle relative to each sensor
- High-performance avionics provide efficient, reliable, and reconfigurable computing environment
- Navigation algorithms provide an optimal estimate of the relative state – position, velocity, attitude, and rate – based on data from all the sensors

Two-year mission provides upwards of 60 relative navigation tracking events (rendezvous and departures).







High-speed, Fault Tolerant Computing
Technology Maturation and Test Campaign

2005-2009 **2010** **2011** **2012** **2013** **2014** **2015** **2016** **2017**

Real-time 6-DOF pose of HST

SpaceCube 1.0 (MISSE-7)

SpaceCube 2.0 STP-H4

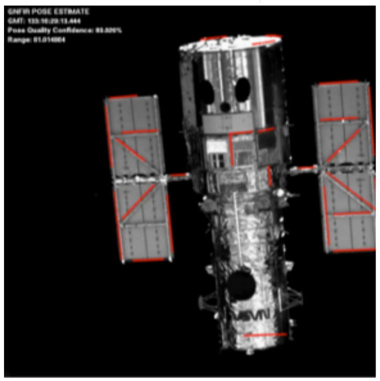
RPO, Real-time, Closed-Loop Testing

Flight processor executing robot control algorithms

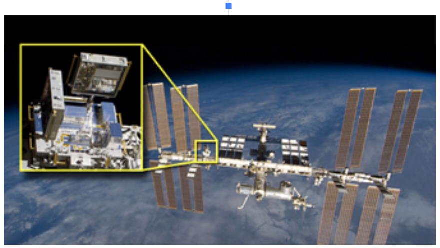
Comprehensive Refueling Tasks

SpaceCube driving Eng. Arm

Raven

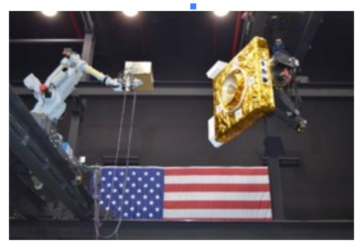


First flight of SpaceCube 1.0, demonstrated non-coop, vision-based nav

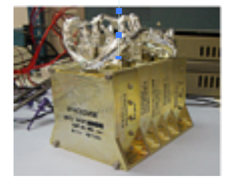


First operational use of SpaceCube 1.0

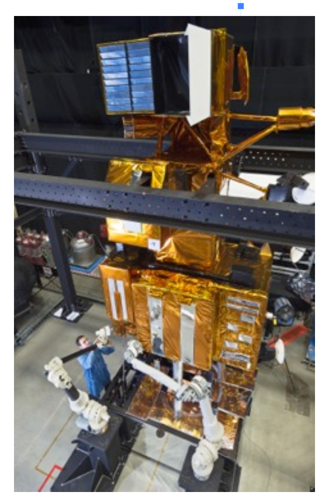
First flight of Virtex 5 FPGA as part of SpaceCube platform



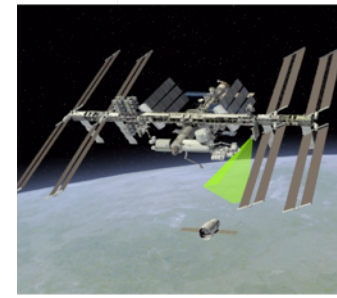
SpaceCube used for closed-loop RPO demos



SpaceCube emulator used for joint control



SpaceCube used for teleop control of EDU conducting servicing tasks



SpaceCube 2.0 EM integrated for Raven – real-time processing of natural feature vision algorithms

Dexterous Robotics
Technology Maturation and Test Campaign

2005-2009 **2010** **2011** **2012** **2013** **2014** **2015** **2016** **2017**

3-DOF Capture

Zero-G 6-DOF auto tracking

Contact Dynamics Validation

Refueling Procedure Validation

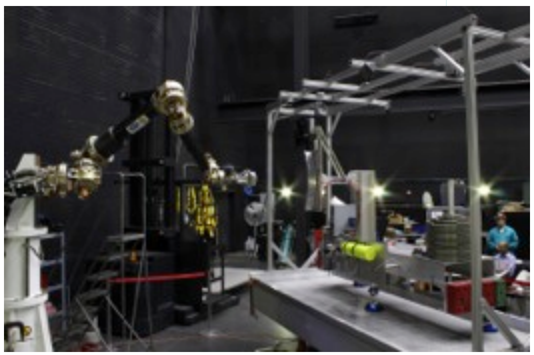
Remote control w/ oxidizer

Receipt of 7-DoF Eng Arm

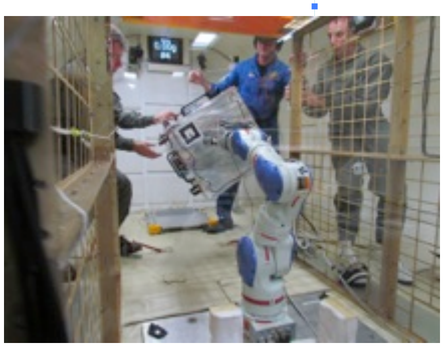
Comprehensive Refueling Tasks

Engineering arm w/ flight-like algorithms

Receipt of 7-DoF –space qualified Arm



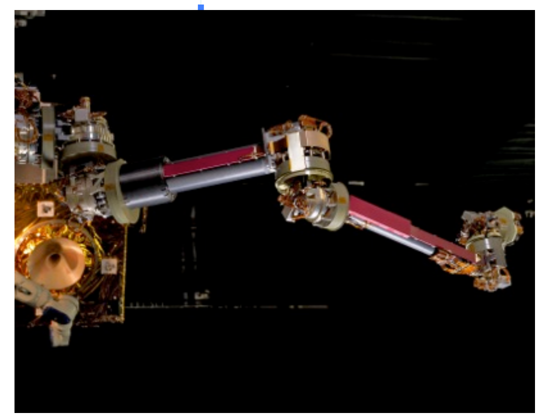
3-DOF Capture tool evaluation at NRL



Autonomous Tracking in zero-G – tracking algorithms and closed loop control

Remote teleop with time delay during hazardous operations

Qual arm for flight



EDU arm arrives at GSFC

Advanced Robotic Tools and Tool Drive

Technology Maturation and Test Campaign

2005-2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

Gripper Tool (2010)

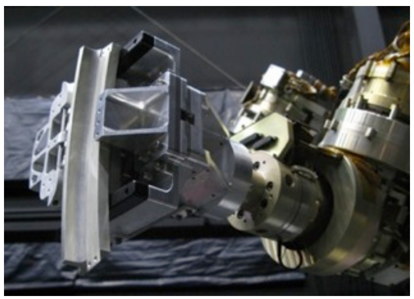
Four RRM tool on-orbit validation (2013)

Oxidizer Tool validation (2014)

Leak Locator shipped (2015)

Inspection tool ops (2015)

Next-gen refueling tools (2016)



Early prototype Gripper Tool

Wire Cutter Tool

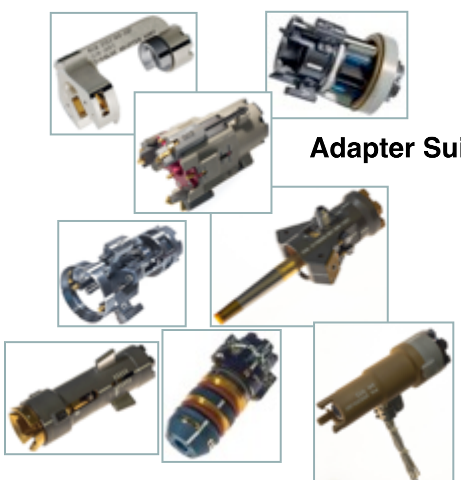
Safety Cap Tool

Multifunction Tool

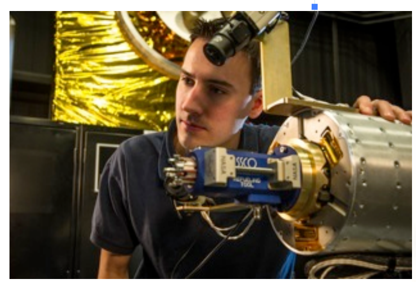
EVR Nozzle Tool

Ammonia Leak Locator, awaiting launch

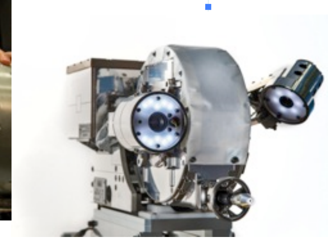
MLI Gripper Tool



Adapter Suite



Oxidizer Nozzle Tool with ATDS visible (right)



VIPIR (Visual Inspection Poseable Invertebrate Robot)

Fluid Transfer

- **The Challenge**
  - Provide fluid on orbit to spacecraft not designed for servicing
  - Wide variation in properties of various commodities (cryo, corrosive, high-pressure)

- **Subsystem in Development**

Fluids to Transfer

- Chemical Propellants
  - Hydrazine
  - Monomethyl hydrazine
  - Nitrogen tetroxide
- Pressurant
  - GHe
- Cryogenic Fluids
  - Liquid Methane
- Electric Propulsion
  - Xenon

Tested Hardware

- Delivery Methods
  - Pumps
  - Bellows
  - Pressure
  - Pistons
- Flow Meters
  - Ultrasonic
  - Coriolis
  - Balanced orifice
  - Positive displacement
  - Turbine
- Valves, latches and regulators

- **Achievements**
  - Transferred ethanol on orbit (Robotic Refueling Mission)
  - Developed Propellant Transfer System and successfully transferred oxidizer on ground (Remote Robotic Oxidizer Transfer Test)
  - Delivered Xenon to cooperative interface
  - Transferred cryogen on the ground pump-free

Fluid Transfer

Technology Maturation and Test Campaign

2005-2009 | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017**

Oxidizer seal-less pump evaluation

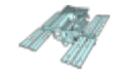
Ethanol refueling on orbit

Hose tests in zero-g, NBL

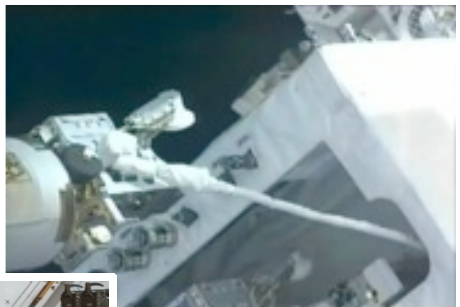
Oxidizer Transfer

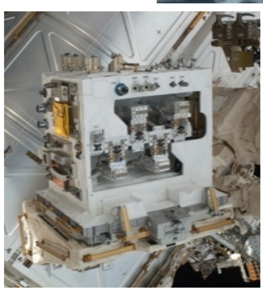
Comprehensive Refueling Tasks

Propellant Transfer system

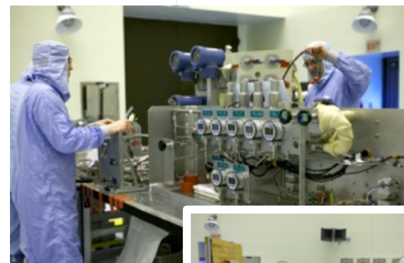


Cryo and Xenon transfer (RRM-3)

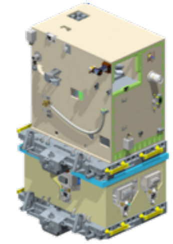




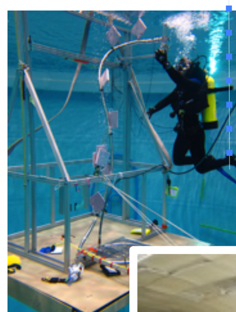
Robotic Refueling Mission demo of tools and procedures and transfer of ethanol



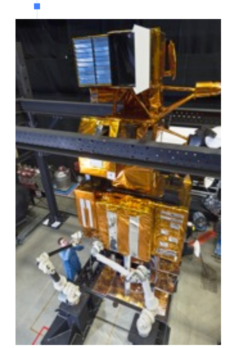
Oxidizer transfer at flight pressures, flow rates and quantities



Demo of xenon recharge & cryogen transfer



Neutral buoyancy and zero-g evaluations of flexible hose characteristics



Propellant Transfer System integrated into system-level test of refueling

Fluid Transfer
Robotic Refueling Mission Demonstrations

RRM is a multi-phased ISS investigation of tools, technologies and techniques for robotic refueling, cryogen replenishment and xenon recharge.

RRM Phase 1

- Storable propellants: steps required to refuel in legacy spacecraft
  1. Take apart components (cut wire, manipulate thermal blankets & fasteners, remove caps)
  2. Connect refueling hardware and transfer fluid
  3. Reseal fuel port
- Cryogen fluid: steps required to replenish cryogens in legacy satellites
  1. Take apart components

RRM Phase 2

- Cryogen fluid: intermediate steps required to replenish cryogens
  2. Connect replenishment hardware

RRM Phase 3

- Cryogen fluid: final steps required to replenish cryogens
  3. Transfer ~50 L
- Cooperative recharge of xenon

Phase 3 data to be shared with:
- *Cryo depot community*
- *ISRU*
- *Advanced ECLLS*

Cryogen Step 1 complete

Propellant Steps 1, 2, 3 complete

Cryogen Step 2 Complete

Cryogen Step 3 & Xenon planned

2011 **2012** **2013** **2014** **2015** **2016** **2017**

Phase 1 **Phase 2** **Phase 3**

Cooperative Servicing Aids (CoSA) Options

CoSA: features that could be incorporated into new satellites to facilitate servicing in the future.

Rendezvous and Proximity Operations

- Features and techniques to increase the reliable and robust rendezvous sequence

Capture

- Features and markings on client tailored to the capture technique going to be employed by servicer

Refueling / Replace

- Design external and internal propellant system to be accommodating of refueling

Placing servicing aids on new spacecraft is an inexpensive way to hedge for a future servicing mission.

CoSA Technology Path

SSCO is developing cooperative interfaces and systems in six key areas.

Capability	Type	Development Avenue
Rendezvous	Autonomous	Raven
Capture	Autonomous	Ground testing and zero-G
Refuel	Hypergol	RRM & ground testing
Recharge	Xenon	RRM3
Replenish	Cryogen	RRM3
Replacement	Modules	ROSE, WFIRST, IRAD effort

Implementing CoSA

Six Months to Launch (or less)

Low Level of Spacecraft Modification (examples)

- Addition of optical / reflective targets on docking / capture axis (adhesive decals)
- Add reference markings around Marman ring (clock-face tic marks)
- Standardize loop size and color (to maximize contrast) of Fill / Drain Valve safety wires

Between PDR and CDR

Medium Level of Spacecraft Modification (examples)

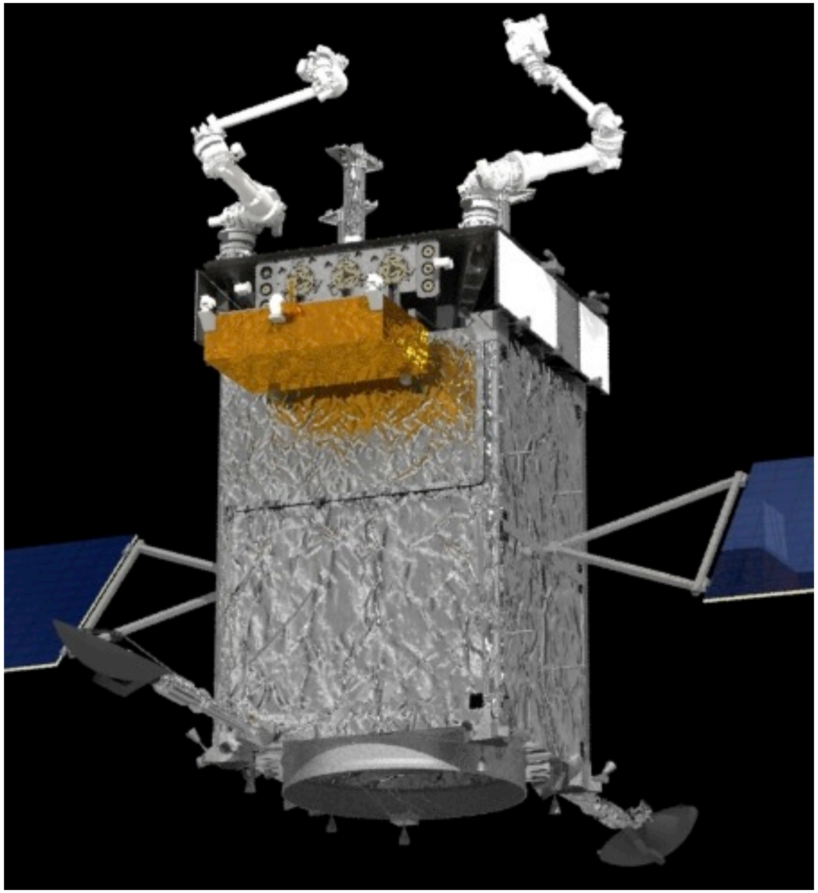
- Install hemispherical retro reflectors for long-range targeting
- Establish spacecraft servicing mode in flight software
- Install robotically compatible “quick disconnect” on Fill / Drain Valve prior to launch

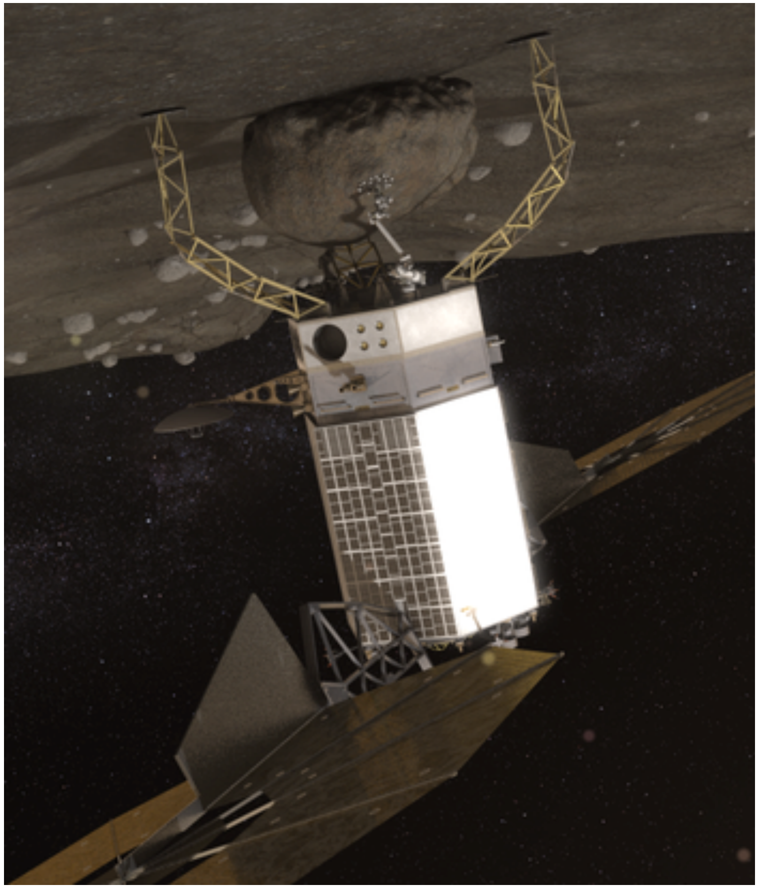
Phase A to PDR

High Level of Spacecraft Modification (examples)

- Add omnidirectional, low power radio frequency beacons
- Redesign Fill / Drain Valve to be compatible with robotic interface
- Incorporate module design for unit replacement

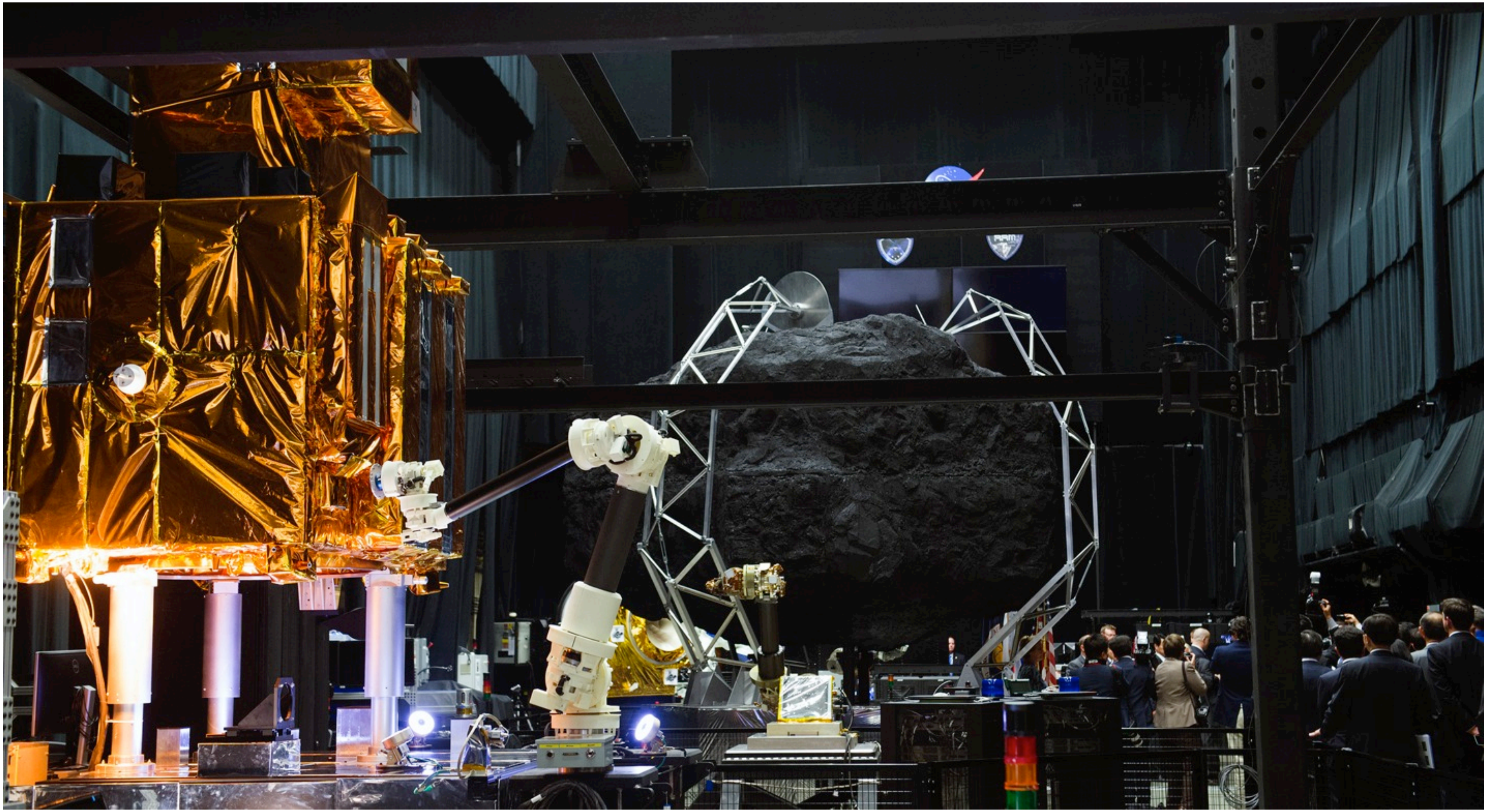
ARM is Utilizing Servicing Technologies





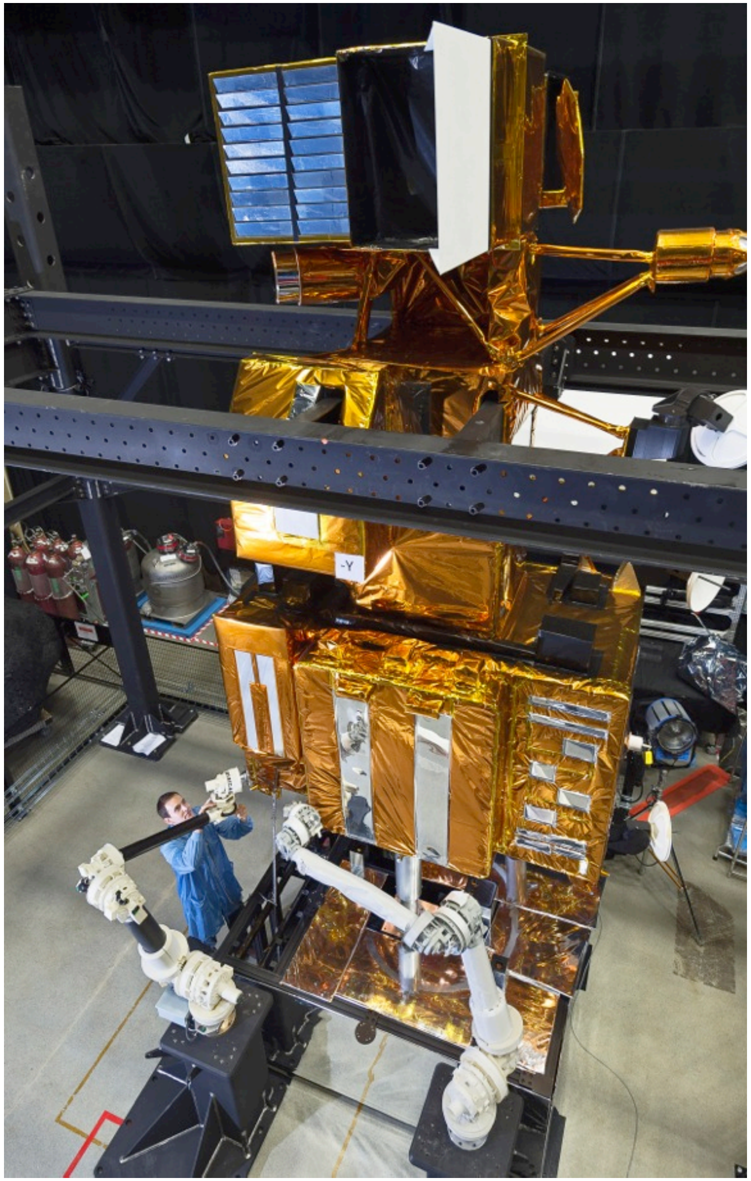
Investments in servicing technologies are paying off.

The Cauldron

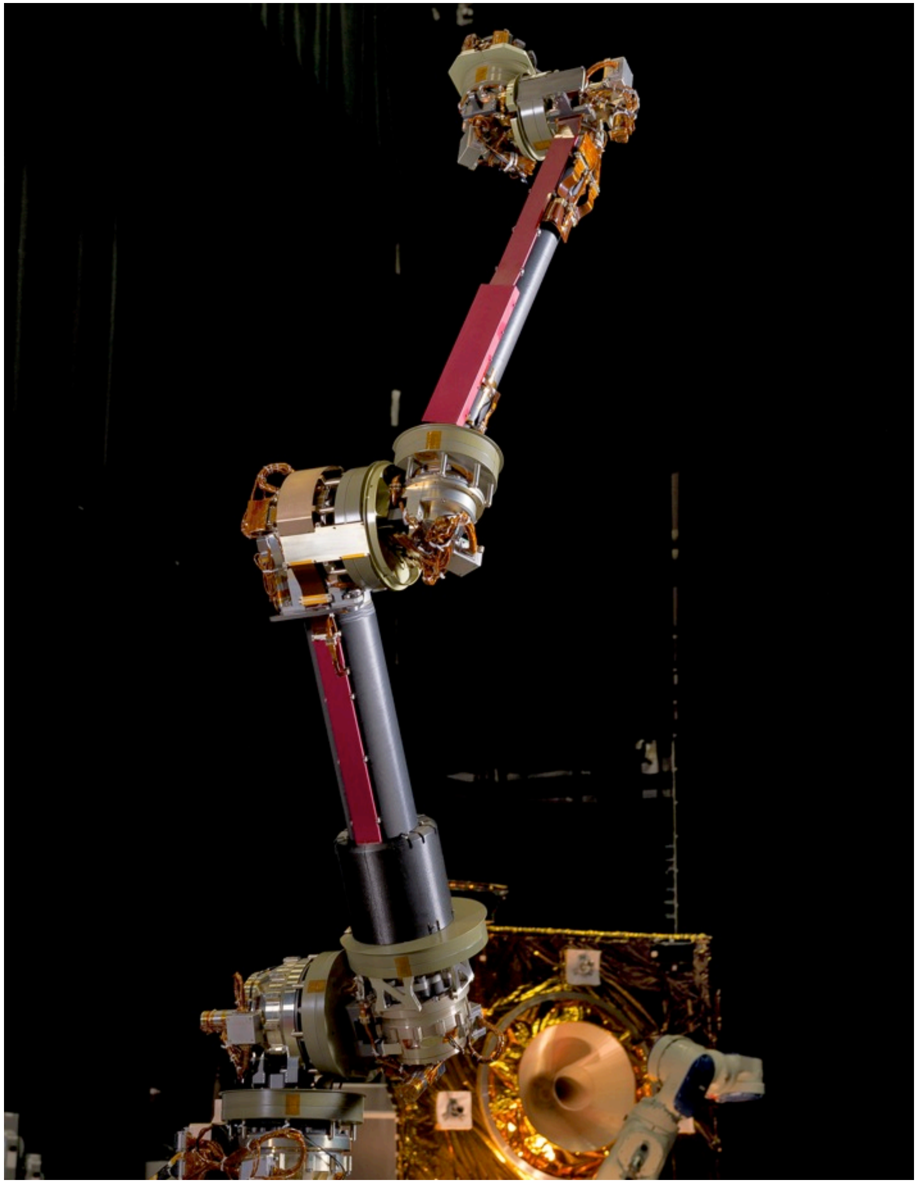


Overview of Room

The Cauldron



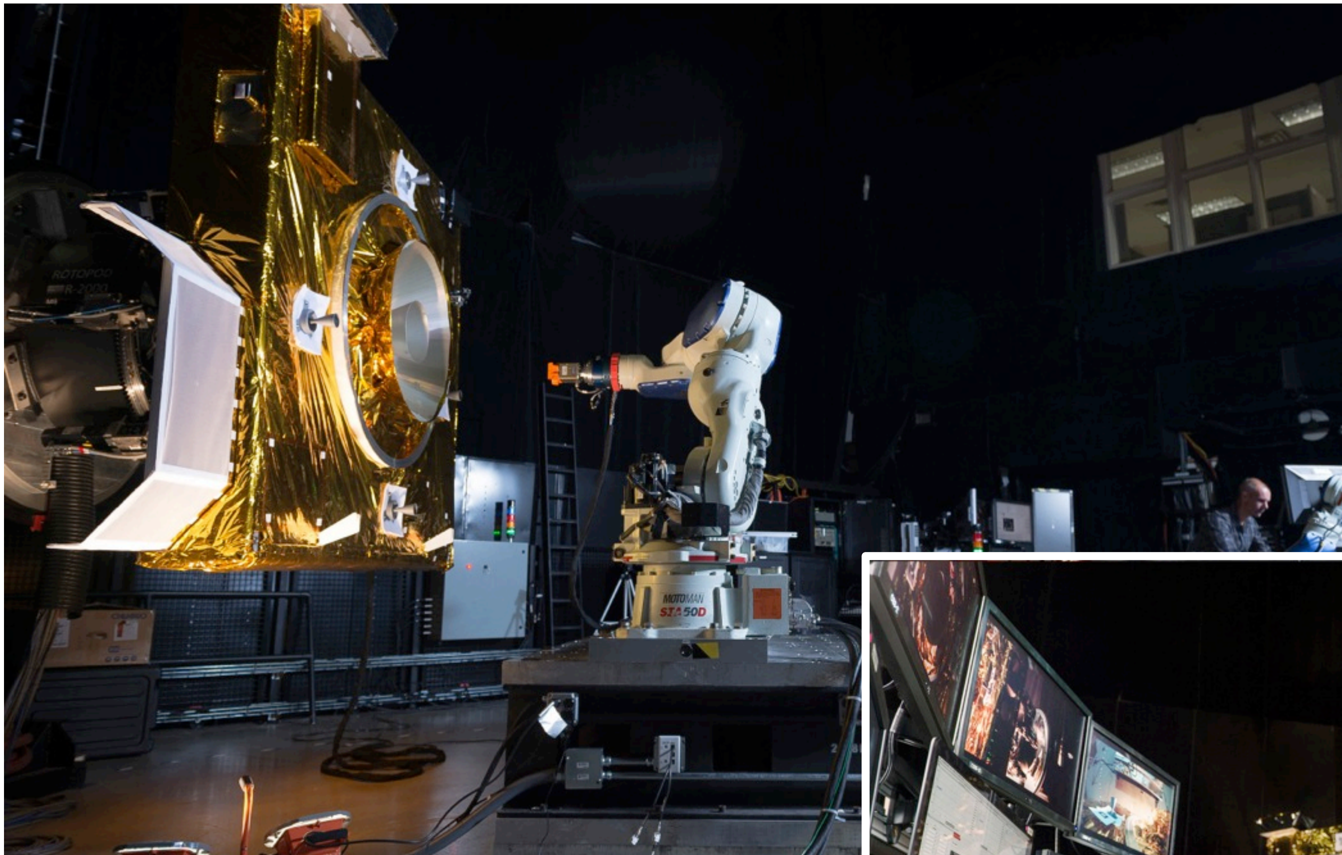
Servicing Technology Development



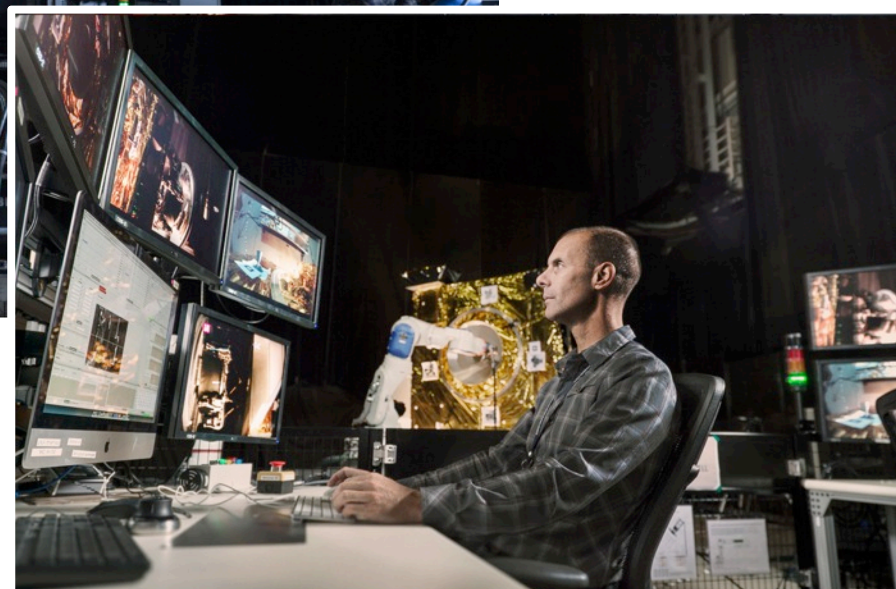
NASA Servicing Arm

The Cauldron

The Cauldron



Robotic Simulations and Technology Development



Looking Forward

- NASA is taking the long view to foster an enduring, expanding domestic industry and stimulate the U.S. economy by extension
- NASA's servicing technology efforts have yielded a return on investment of 16 patents and growing. NASA brings this IP and more to the table to foster and nurture a robust new industry.
- NASA's in-space robotic servicing efforts deliver a portfolio of advanced, flight-tested technologies that directly benefits NASA missions

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